AN ASSESSMENT OF LIFTING REENTRY FLIGHT CONTROL REQUIREMENTS DURING ABORT, TERMINAL GLIDE, AND APPROACH AND LANDING SITUATIONS

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SUMMARY

The results of the X-15 research airplane and M-2 lifting-body flight programs and various simulation programs are summarized for pertinence to the control requirements for manned lifting reentry. Piloted reentries have been successfully accomplished with several degrees of control-system sophistication and at a variety of reentry conditions, some more severe than expected during orbital reentry. Control requirements for terminal glide are indicated to be less severe than those for high-performance aerodynamic vehicles. Approach and landing of unpowered low-lift-drag-ratio $\left(\frac{L}{D}\right)$ *vehicles is well within the pilot's capability. Initiation of the landing flare at airspeeds greater than the speed for maximum lift-drag ratio proved to be an effective landing technique for accurate landing of low* $\frac{L}{D}$ *vehicles.*

1. INTRODUCTION

Thus far, the United States has had manned orbital reentry flight experience with the Mercury and Gemini capsules. As successful as these programs have been, the initial endeavors leave something to be desired from the pilot's viewpoint.

Consider the maneuverability available during a hypersonic reentry. Fig. 1 compares maneuverability limits or "footprints" associated with various reentry vehicles. The Mercury and Gemini vehicles have extremely limited maneuverability associated with a hypersonic maximum lift-drag ratio $\left(\frac{L}{D_{max}}\right)$ of 0 and 0.25, respectively. On the other hand, a truly lifting reentry vehicle, such as the M-2 or HL-10 lifting body, may have a hypersonic $\frac{L}{D_{max}}$ of 1 to 1.3. The vastly increased range envelope shown by the larger footprint associated with this $\frac{L}{D}$ would enable a landing to be made at virtually any base in the continental United States on a single pass. In addition to the higher lift-drag ratio, the M-2 and HL-10 vehicles shown in Fig. 2 are also capable of horizontal landing on prepared runways. Because of the greater operational flexibility offered by a lifting reentry vehicle, the major emphasis of this paper is on this type of aerospace vehicle.

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Although no manned lifting reentry from orbital speeds has yet been performed, numerous simulator studies of proposed missions have been made, including comprehensive evaluations of lifting bodies. In addition, the X-15 hypersonic flight tests (1, 2)* and M-2/HL-10 flight programs (3) have provided a basis for assessing certain regions of the reentry flight envelope in a realistic environment.

This paper examines piloting factors in the overall lifting reentry flight control task with particular emphasis on reentry, terminal glide to base, and approach and landing. Among the items to be discussed will be control-system requirements, control-power design levels, required maneuverability, and the degree of simulation sophistication needed.

2. FLIGHT CONTROL REQUIREMENTS

2.1 Reentry

The reentry of a lifting vehicle into the atmosphere consists of several phases which require longitudinal trim changes and possibly bank-angle variations. For the orbital vehicle these phases are distinct, and preparation for each may be accomplished in time by the pilot. In the only lifting reentry vehicle with which we have extensive experience, the X-15 research airplane, all the phases of reentry are compressed into a very short time, as indicated in Fig. 3. This figure compares an orbital lifting-body reentry with that of the X-15 for reentries from similar altitudes. The X-15 reentry is more severe, as is indicated by the level of acceleration and dynamic pressure. For the X-15 reentry, planning is vital for, unless the proper technique is used, the pilot could exceed the design dynamic pressure and acceleration. There are, of course, recovery situations (4) from abort during orbital launches that the X-15 reentry more nearly duplicates. Fig. 4 compares the X-15 reentry from 285,000 feet and an M2-F2 simulated lifting-body reentry following abort during first-stage launch. The timing of the reentry phases is very similar, as is the level of acceleration required for pullout; however, the lower $\frac{L}{D}$ vehicle pulls out with somewhat lower dynamic-pressure buildup than the X-15 airplane.

In addition to the X-15 flight experience during the high-altitude flights where dynamic pressure is very low, much additional X-15 experience has been obtained during aerodynamic research flights that may be applicable to the various phases of reentry flight.

The setup prior to atmospheric reentry (5) must be accomplished by the use of reaction or ballistic controls. The control task in a lifting vehicle involves achieving and maintaining zero sideslip, a positive angle of attack, and a constant bank angle. The requirements of a ballistic control system may vary considerably for each vehicle, and optimum rates or control modes are not easily defined. Real-time mission simulation appears to be the best means of obtaining design information.

X-15 experience indicated that the pilot could successfully accomplish the setup control task for reentry with the simplest type of ballistic control system--a constant-thrust, on-off control in all three axes. However, to reduce the pilot's workload and to minimize vehicle oscillations at low dynamic-pressure conditions, rate damping was subsequently added to the system. The pilots appreciated the increased damping but disliked the rate dead band which was designed into the system to conserve reaction control fuel. The dead band allowed low drift rates in

*Numbers in parentheses are reference numbers.

all axes. Attitude hold or autopilot modes were evaluated by the pilots to be somewhat superior to the simpler systems and required less pilot concentration.

With the X-15, reentries have been made with each of two variations of two basic control systems. Two X-15 airplanes are equipped with conventional aerodynamic controls with stability augmentation and acceleration command reaction controls. Backup aerodynamic damping augmentation has been added for redundancy, and reaction augmentation has been added for increased controllability at low dynamic pressure. Another X-15 airplane is equipped with an adaptive control system, the MH-96 flight control system, which was developed under Air Force contract for evaluation in advanced vehicles. The X-15 program provided the opportunity to evaluate the design capabilities of the system in actual reentry flight. The system has adaptive gain-changing rate command aerodynamic and rate command reaction controls in all three control axes, blended aerodynamic and reaction controls, attitude command or hold modes, and normal-acceleration limiting.

The X-15 reentry control task requires the pilot to establish and hold the desired angle of attack until normal acceleration builds to the desired value, and then to hold normal acceleration until a constant glide angle of attack or constant rate of descent is achieved.

By means of this control technique, reentries from high altitudes have been made to cover a wide range of reentry parameters (4). Fig. 5 shows average values of reentry angle of attack, maximum values of normal acceleration, and maximum dynamic pressure. These values are not unique functions of the maximum altitude, since they may be altered by piloting technique; however, they represent the reentry experience obtained to June 1966. The design altitude of 250,000 feet is shown for reference. Reentry angle of attack has varied from about 12° to 20° during reentries from the lower altitudes. During reentries from higher altitudes, angles of attack up to about 25° were used. The use of reentry angles of attack higher than these values is not planned, inasmuch as trim capability is limited because of the increased static longitudinal stability at high angle of attack. Also, some control must be reserved for the stability augmentation system.

A range of normal acceleration of only about 3g to 5g has been used, since higher accelerations were not required for recovery and there was no need to test to the design limit of the airplane. A wide range of reentry dynamic pressure was covered, inasmuch as this quantity is more critically dependent on piloting technique. Maximum reentry dynamic pressure was about 1900 lb/sq ft.

Reentries have been accomplished in a variety of reentry environments and with several degrees of control-system sophistication. A comparison of reentry controllability with the most and the least sophisticated control systems is shown in Fig. 6. Fig. 6(a) shows a reentry with the pilot flying manually using the conventional control system, which has acceleration reaction controls and aerodynamic damping augmentation. In Fig. 6(b) the pilot is using the adaptive control system with attitude-hold modes operative. This system also has command reaction controls that are automatically blended with the aerodynamic controls.

The most significant difference between the two reentries is the magnitude of the angle-of-sideslip oscillation as normal acceleration and dynamic pressure build up. The excursions are smaller and the controllability was superior with the higher-gain system. The reentries were made by different pilots; however, their evaluations of the reentry control tasks were similar: satisfactory, with a slight deterioration in the lateral-directional mode. At angles of attack higher than achieved during these reentries, however, the controllability of the airplane with the adaptive control system is predicted on the X-15 simulator to be clearly superior.

The pilots' average rating of pitch, roll, and yaw controllability with the various control systems is summarized in the following tabulation:

	Flights	Pilots	Average pilot rating
Conventional (stability augmentation system)	3	3	2.0
Conventional (stability augmentation system, reaction augmentation system)	6	4	2.4
Adaptive	12	3	1.6
Adaptive, hold	2	1	1.8

Although reentry controllability with all the controls was rated satisfactory, the adaptive rate command controls were rated superior to the other controls. The conventional controls with reaction augmentation were rated the least satisfactory; however, the pilots did appreciate the addition of the reaction damping. All flights to high altitude, since the addition of reaction augmentation, have been made with this system. Only a limited number of reentries have been made with the adaptive system hold modes; however, these control modes have been used more extensively in other phases of flight. Pilot opinion on the use of hold modes is varied. These modes greatly reduce the pilot's concentration and workload, but some pilots prefer to be active in the control loop at all times. An acceptable compromise preferred by some is active control of the primary control mode, pitch, and the use of attitude command in roll and yaw.

The amount of control used during X-15 reentries is summarized and compared to the control available in Fig. 7. The aerodynamic control angular acceleration used in pitch, roll, and yaw includes the critical setup period prior to dynamic-pressure buildup through pullout to a constant glide angle of attack or rate of descent. The controls used include both the pilot and the augmentation system.

A much higher percentage of available aerodynamic control was used in pitch, primarily for trim to establish and hold angle of attack, than was used in the other control modes. During the initial part of the reentry, nearly 100 percent of the control available was used to initiate pullout, but, as dynamic pressure increased and the pullout developed, a lower percentage of control was required. The control used in roll and yaw was low and was for stabilization. Similar requirements for stabilization in pitch were indicated. Reaction controls were used during the first part of the reentry. Reaction controls with an authority of only about 1 percent of the maximum available aerodynamic controls were found to be completely satisfactory.

In an orbital reentry, dynamic-pressure buildup will be of much longer duration, and small errors in trim angle of attack or angle of sideslip can be eliminated before short-period oscillations are initiated. Also, the pullout phase in an orbital reentry will be much less severe than in the X-15. Reentry will involve more gradual flight-path changes and much lower normal accelerations and dynamic pressures. High reentry attitudes will be required, however, which means high trim capability.

In an orbital reentry with the M-2, the deceleration time to equilibrium glide is increased significantly over the X-15 experience; thus, trim, rather than maneuvering with normal stick control, would be desirable. Control-surface rates required would be very low, and the probability of inducing a longitudinal oscillation would be small.

Prior to actual piloted reentry flight, many questioned the capability of the pilot to control under high reentry accelerations. Early in the X-15 project, centrifuge programs were initiated to determine if the reentry acceleration would affect the pilot's control performance. These simulations and subsequent flight tests showed that, when adequate support and restraint were provided, the reentry acceleration did not affect the pilot. The pilots have since concluded that the exposure to the high simulated reentry acceleration was not necessary; however, it did give them increased confidence that they could control through that acceleration environment. For acquaintance with, and practice of, planned flight missions, a fixed-base cockpit simulator has been adequate for all flight preparation. One possible exception was the pilot-induced oscillation with the dampers-off, ventral-on configuration. The fixed-base simulator for this configuration, with the pilot using a special control technique, gave an optimistic indication of the controllability compared with that experienced in actual flight, since it provided no kinesthetic or outside visual cues. In this case, the acceleration environment was detrimental to control.

2.2 Terminal Glide

The terminal glide (6) from reentry begins at the initiation of equilibrium glide and ends when the pilot acquires the destination by radio aids, sight, or other means. The pilot's control task may be completely longitudinal or combined with roll to achieve lateral displacement. The control rates required are very low, since banks of long duration will be required to achieve lateral displacement. Longitudinal control will also require only low rates, inasmuch as deceleration is slow and trim rates for control should be completely adequate. Aerodynamic stability-augmentation requirements will be minimal and reaction stability augmentation may be adequate. Pitch augmentation only may be required.

When the pilot acquires the destination, a final heading-change correction may be required because of guidance inaccuracies; however, the flight-path corrections should not be excessive. This maneuvering may also involve a transition from the back side to the front side of the $\frac{L}{D}$ curve.

In addition to the reentry experience with the X-15 airplane, many flights have been made to hypersonic speeds for research purposes. Several glide recovery techniques have been investigated. Some of these techniques were to maintain constant aerodynamic conditions for heating data and constant rate of change of altitude for controlling range by flight-path control.

Terminal glide and maneuvering (2, 4) with the X-15 airplane is done on the front side of the $\frac{L}{D}$ curve, and speed brakes have been used extensively to adjust the energy. The flights are planned and practiced on a simulator to acquaint the pilot with all variations in the flight plan likely to be encountered in flight. Piloting rules of thumb for energy management are developed which substitute for guidance information. The low turn rates available at high speed provide useful piloting experience. With the methods used to date, no actual display of range capability has been necessary, but a display of computed range capability is being mechanized for future flights for research purposes and would furnish information applicable to instrument flight rule (IFR) situations. Flights have always been planned with some excess range, and the pilots have had no difficulty in controlling to the range required.

The X-15 recovery technique will be representative of a lifting-reentry-vehicle approach to the landing site from the initial conditions of 100,000 feet and a Mach number of 5. Although reaction controls may be used during the initial phase of reentry at higher Mach numbers, aerodynamic controls are expected to be used for the control of airplane attitude while controlling range and approach to landing.

The aerodynamic controls used and the maneuvering required during the X-15 recovery from Mach 5 to landing is summarized in Fig. 8. Note that the Mach number is highest at the right, decreasing to landing speed to the left. Only small bank angles and low roll rates were used by the pilots during the stabilized high Mach number portion of the recovery. Less than 10 percent of the roll control available was used. About 40 percent of the longitudinal control available was used for trimming to the desired angle of attack for control of range.

At the lower Mach number, significantly more bank angle and roll rate were used for terminal maneuvering; however, a much lower percentage of control available was used in both roll and pitch, inasmuch as effectiveness is higher and much less control is required for longitudinal trim. From these results it can be inferred that hypersonic maneuvering during the recovery of reentry vehicles will require substantially less control than conventional fighter-aircraft maneuvering, inasmuch as maneuvering is minimal except during landing approach.

2.3 Approach and Landing

The control task during approach (6, 7) is to maneuver the vehicle to a location short of the desired touchdown point and to arrive at this position with sufficient energy to accomplish a flare. For the purposes of this discussion, it is assumed that propulsion will not be available. Experience has shown that the pilot can reliably complete a manual unpowered approach with a minimum of information if he can see the desired touchdown location throughout a major portion of the approach. Unpowered vehicles having maximum lift-drag ratios of 2.8 and wing loadings of 75 lb/sq ft have been satisfactorily maneuvered to a desired flare-initiation location. Unpowered night approaches at a maximum $\frac{L}{D}$ ratio of 4.0 and a wing loading of 40 lb/sq ft have been demonstrated, and we are confident that techniques can be developed for unpowered instrument weather approaches.

The visual approach preferred by the pilots in the daylight has been an overhead circling approach, as shown in Fig. 9. The approach begins over an aim point at an altitude determined from computation or simulation of the vehicle's performance characteristics. The initial approach conditions are normally established for a given vehicle airspeed and bank angle. A nominal pattern is thus defined in terms of altitude versus pattern position. A constant indicated airspeed is used to simplify the pilot's task and accounts for the variation in turning radii. The pilot memorizes various checkpoint altitudes throughout the pattern and varies turning rate as necessary to achieve these desired conditions.

The pilot can vary airspeed (or equilibrium lift coefficient) to adjust the pattern and can, if necessary, increase the lift coefficient to that for $\frac{L}{D_{max}}$ to stretch the glide. This varying-lift technique has been used occasionally in actual X-15 approaches, but a preferred technique is to fly the pattern in a manner that allows the use of speed brakes for drag adjustments. This results in a higher high-key altitude or closer-in pattern than without speed brakes and insures that the pilot will not land short of the runway. Speed brakes are used when the pilot definitely assures himself that he can reach the runway.

A nominal pattern at an airspeed in excess of that for $\frac{L}{D_{max}}$ and using speed brakes has been very successful for low $\frac{L}{D}$ approaches and has resulted in touchdown errors of less than 1000 feet for routine landings at Edwards, California, in the X-15 airplanes, as is shown in Fig. 10. Even less error could be achieved with faster-acting speed brakes. The pilot used high bank angle to keep the runway in sight and to control pattern ranging. Even with high bank angles, normal accelerations are low because of the rapid descent. Longitudinal control rates up to 10 deg/sec are used to obtain vehicle pitch rates of 3 to 5 deg/sec.

The X-15 pilots have not used the maximum control (4) or maneuvering capability of the airplane longitudinally and have used only a small percentage of the available roll, yaw, or pitch control. If these same vehicle rates and normal accelerations are available in a lifting reentry vehicle, the pilot should be completely capable of performing an unpowered approach to a selected runway.

The control task during the final phase of a reentry vehicle glide flight is to arrest the vehicle's velocity just above the landing surface and land at an acceptable airspeed and attitude. Experience at the NASA Flight Research Center has indicated that the pilot can accomplish an unpowered flare successfully if direct vision is available, even in vehicles with relatively poor performance characteristics. The minimum preflare flight-path angle for these vehicles was approximately -20°, and the minimum rates of sink exceeded 100 ft/sec and may have been as high as 400 ft/sec.

Fig. 11 illustrates the importance of proper selection of preflare airspeed (3, 7). The flare on the left was initiated from an airspeed equivalent to $\frac{L}{D_{max}}$. The flare on the right was initiated from an airspeed well in excess of that for $\frac{L}{D_{max}}$. During the flare, airspeed was decreasing at a rapid rate. In each case, approximately 50 knots were lost before zero flight-path angle was reached. The load-factor variation used by the pilot is shown for each flare and, since this is a function of airspeed, the flare initiated at higher airspeed provides the pilot with the most load factor available. The higher preflare airspeed is obtained at the expense of a steeper flight-path angle; however, the time to reach zero flight-path angle and the airspeed lost during flare do not change noticeably. The higher preflare airspeed also improves control effectiveness in all axes and, perhaps of primary importance, provides more float time after flare. It allows the pilot to delay gear deployment (gear deployment decreases $\frac{L}{D_{max}}$) and provides time to adjust height above the ground after the flare. The pilot tends to complete a flare well above the landing surface in the X-15 or M-2 vehicles and, as a result, requires some time after flare to fly down to the runway.

Data obtained from several hundred unpowered flares in various aircraft indicate that the pilot uses an average of about 1.5g to accomplish the flare. The g-level is not constant, however, and varies as much as 0.5g around the average value in response to visual cues during the flare, since visual perception is at its best due to proximity to the ground. The pilot needs and uses a range of load factor throughout the flare and postflare time to achieve good touchdown conditions.

Most touchdowns occur just after an airspeed equivalent to $\frac{L}{D_{max}}$ is reached. Airspeed is decreasing rapidly and it becomes increasingly difficult for the pilot to maintain a level flight path as he exceeds $\frac{L}{D_{max}}$, since control effectiveness is decreasing, flight-path response to control input is changing, and load factor available is decreasing.

Pitch rate available during and after flare is very important and may, in many vehicles, dictate the maximum design rate. Lateral-control response rates may also be dictated by the postflare requirements. Recovery from an upset condition dictates the maximum roll rate required, since, for other maneuvering phases, low roll rates are quite acceptable.

A number of ground-based simulation techniques have been tried unsuccessfully for the simulation of the approach and landing phase of low $\frac{L}{D}$ reentry vehicles. The primary problem is that the visual techniques used are characterized by a loss in resolution as the vehicle approaches the ground. In actual flight the reverse is true. Consequently, operational aircraft such as the F-104 are used for in-flight simulation. These aircraft can be made to closely duplicate the reentry vehicle $\frac{L}{D}$ characteristics through proper power and configurational scheduling. A pilot usually practices simulated approaches and touchdowns in an F-104 airplane the day before an X-15 or lifting-body flight.

3. CONCLUDING REMARKS

The reentry experience obtained to date indicates that the piloted lifting reentry mission, at least from the control standpoint, could be undertaken with confidence. Piloted reentries that are more severe than those predicted for orbital vehicles have been accomplished with conventional piloting and control techniques. Control requirements for orbital reentry are predicted to be less severe than those of high-performance airplanes. Approach and landing techniques have been developed that allow safe horizontal landing of these vehicles at selected landing sites.

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5. SYMBOLS

g	acceleration due to gravity, ft/sec^2
h	altitude, ft
$\frac{L}{D}$	lift-drag ratio
L_{δ_a}	roll acceleration due to aileron deflection, 1/sec^2
M_{δ_h}	pitch acceleration due to horizontal-tail deflection, 1/sec^2
N_{δ_r}	yaw acceleration due to vertical-tail deflection, 1/sec^2
q	dynamic pressure, lb/sq ft
α	angle of attack, deg
δ_a	aileron deflection, rad
δ_h	horizontal-tail deflection, rad
δ_r	vertical-tail deflection, rad

Subscript:

max	maximum

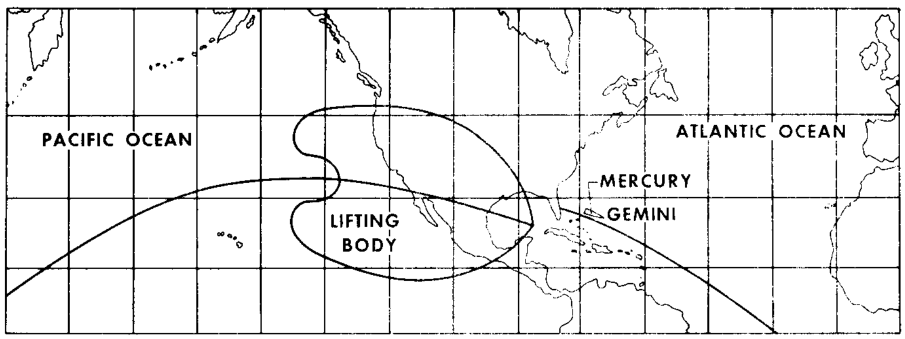

Figure 1.— Orbital reentry footprints.

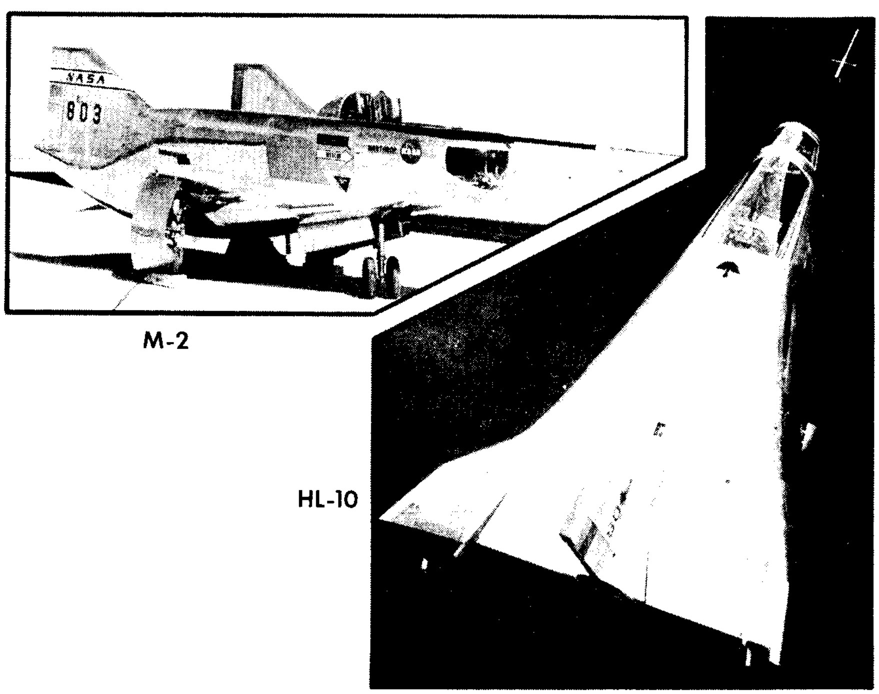

Figure 2.— Lifting-body vehicles.

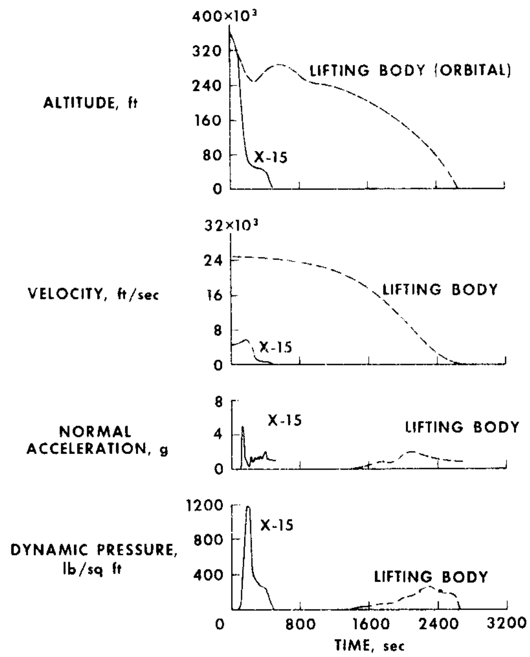

Figure 3.— Comparison of X-15 and lifting-body reentries.

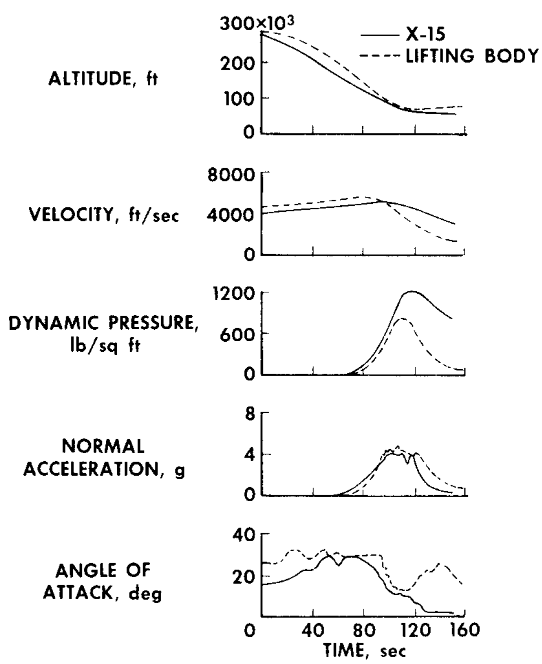

Figure 4. Comparison of X-15 reentry and lifting-body abort recovery.

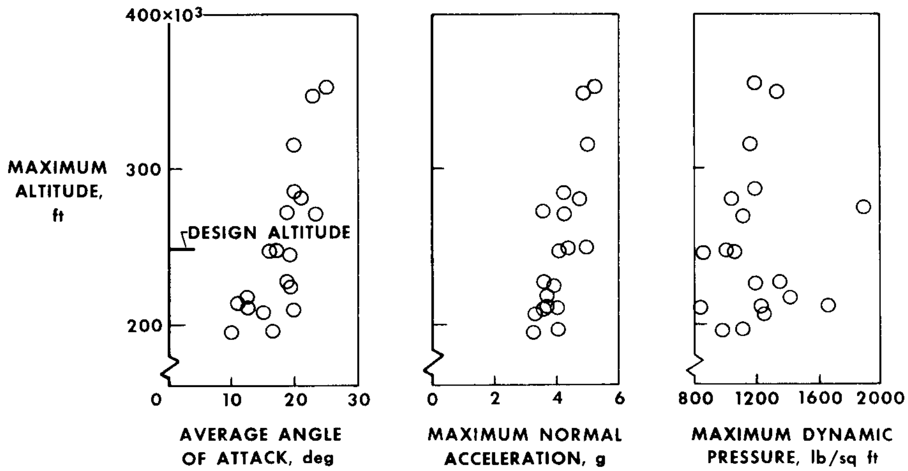

Figure 5.— Range of X-15 reentry parameters.

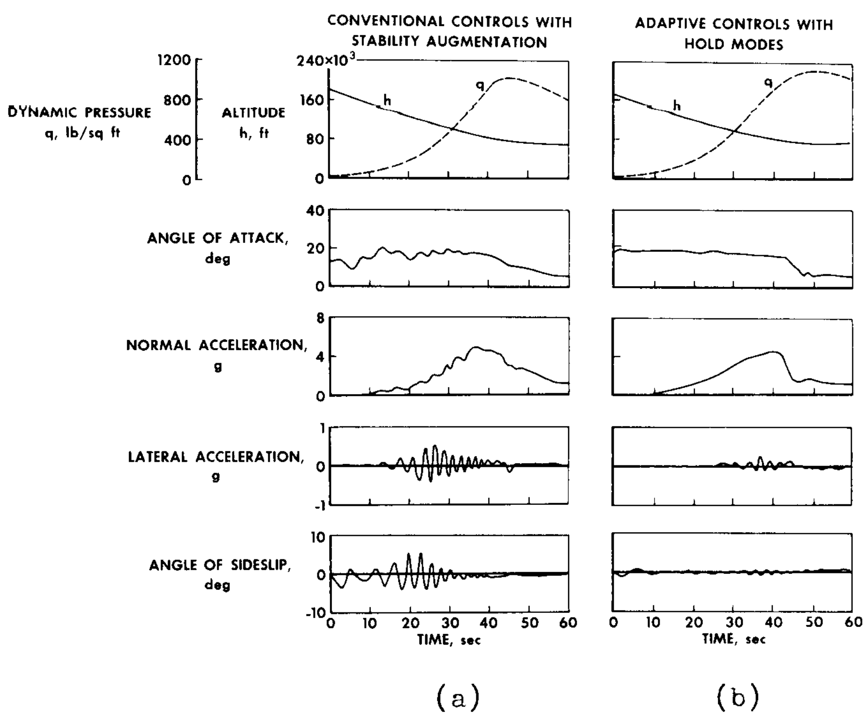

Figure 6.— Controllability of reentry from 250,000 feet with ventral on.

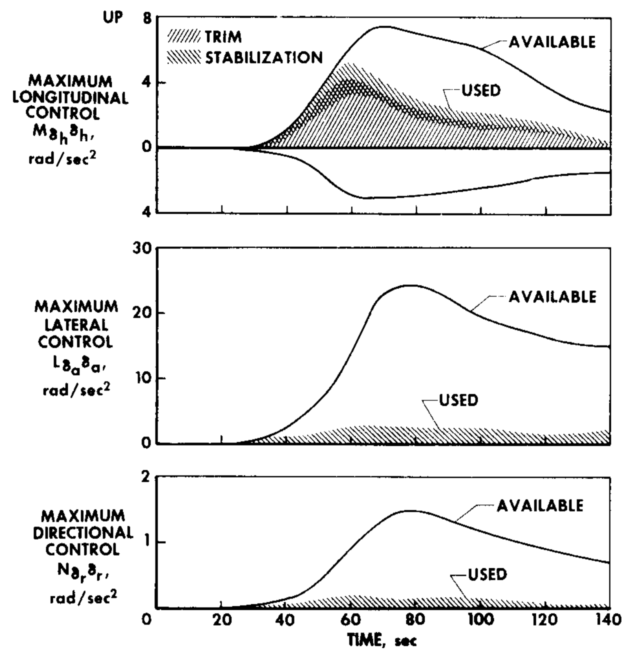

Figure 7.— X-15 reentry controls.

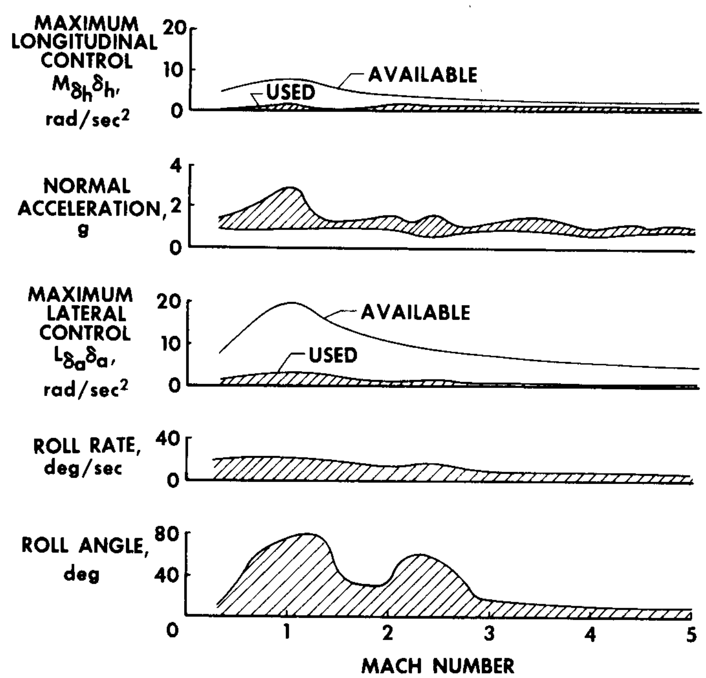

Figure 8.— X-15 maneuvering experience during glide to base.

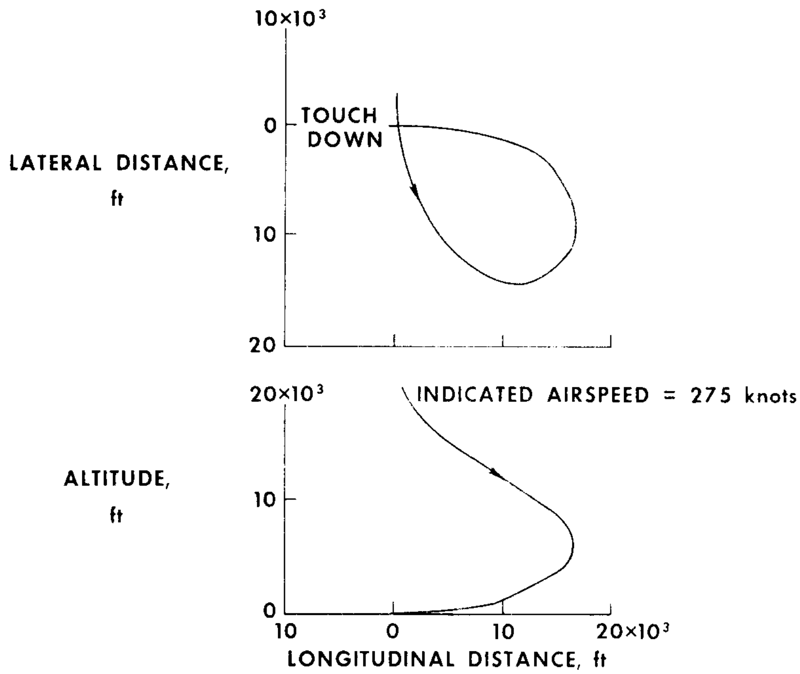

Figure 9.– Typical low $\frac{L}{D}$ circular landing pattern.
$\frac{L}{D}_{max} = 2.8$; $\frac{W}{S} = 75$ lb/sq ft.

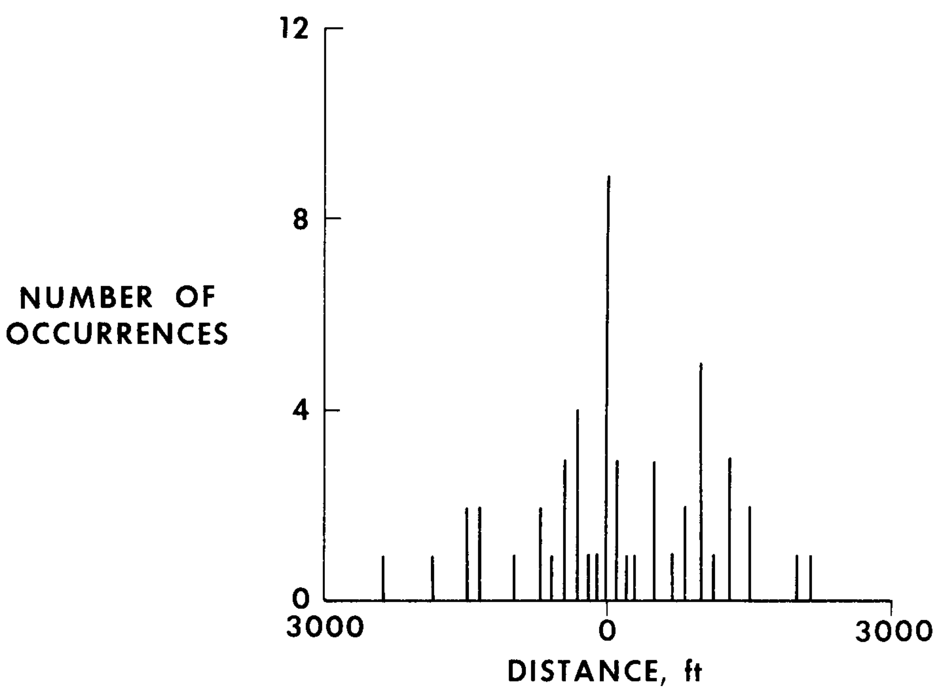

Figure 10.– X-15 touchdown dispersion.

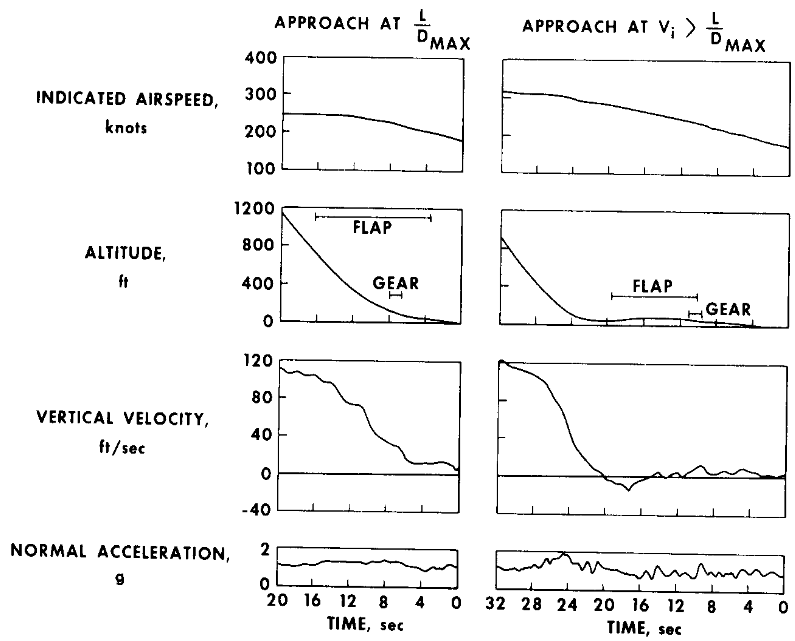

Figure 11.– Comparison of low $\frac{L}{D}$ landing techniques.